Experimental Considerations for Ground-Based Testing of Lunar Construction Technologies

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Introduction

- NASA's Moon-To-Mars Planetary Autonomous Construction Technology (MMPACT) project seeks to research, develop, and demonstrate lunar surface construction capabilities

- Quantification of lunar regolith's geotechnical properties allows for effective prediction of forces and displacement during excavation and construction and is critical to facilitating regolith sintering capabilities all of which benefit lunar infrastructure plans
  - *Knowledge of shear strength, Mohr-Coulomb cohesion, angle of internal friction, bearing strength, bulk density, etc. is needed*

- Ground-based testing of various lunar simulants with relevant hardware (e.g., robotic arm tools) enables validation of technology choices, tool paths, and lunar surface construction activities
  - *Use of Taguchi methods [1] will minimize the number of needed experiments to explore critical input parameters*

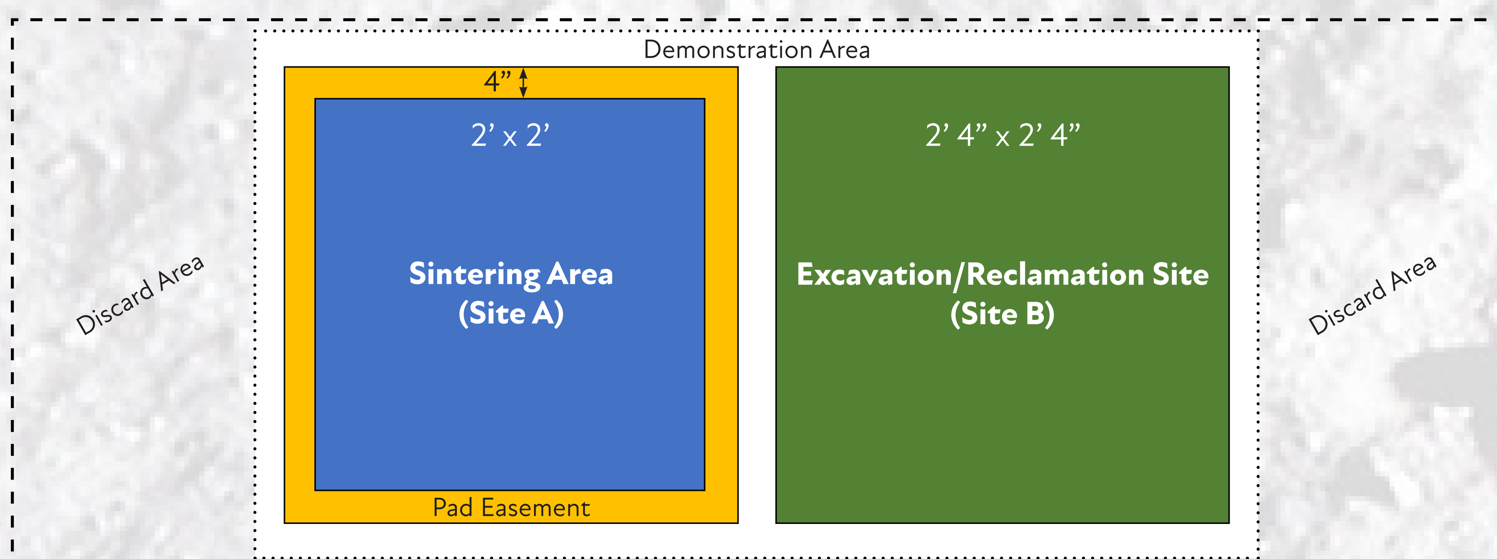

Figure 1. Site Prep Concept of Operations for Microwave Sintering a 4" Thick Demo Pad of Lunar Regolith

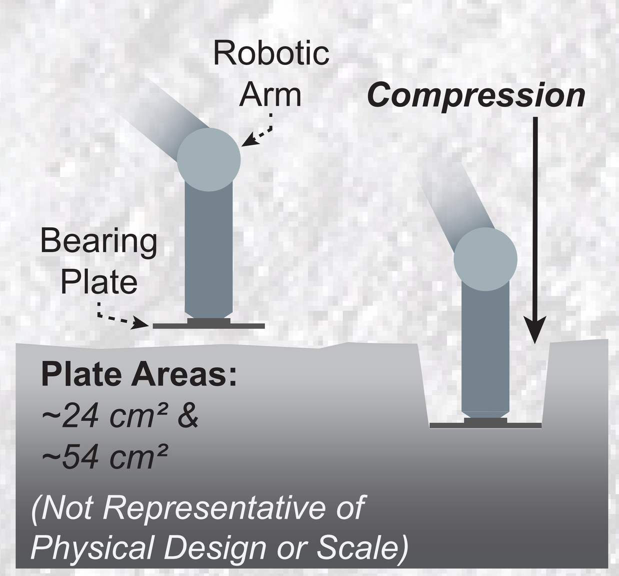

Figure 2. Diagram of Pressure-Sinkage Test

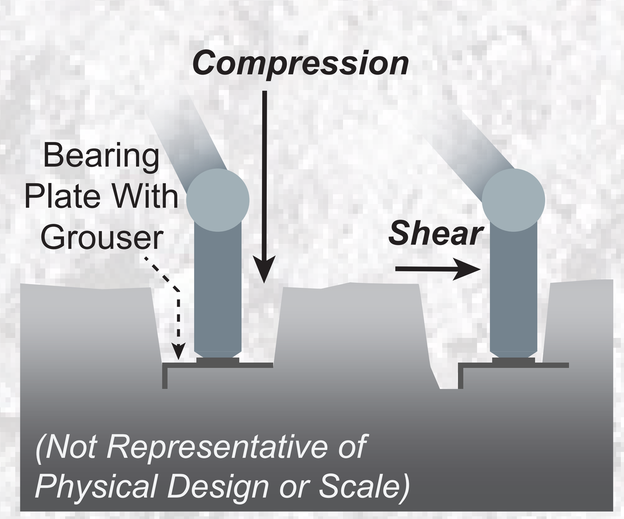

Figure 3. Diagram of Shearing Test

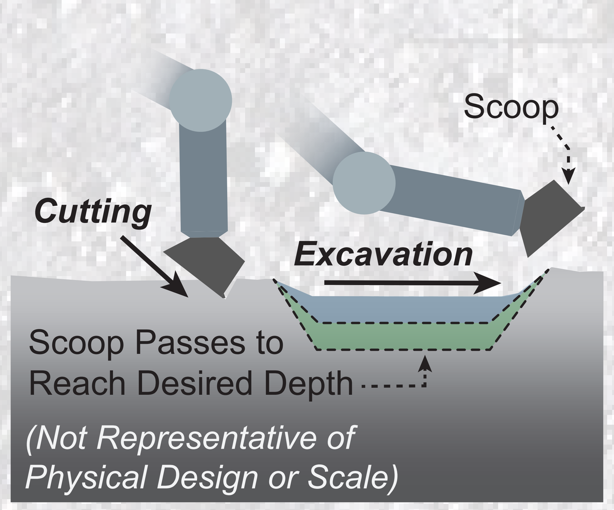

Figure 4. Diagram of Excavation Test

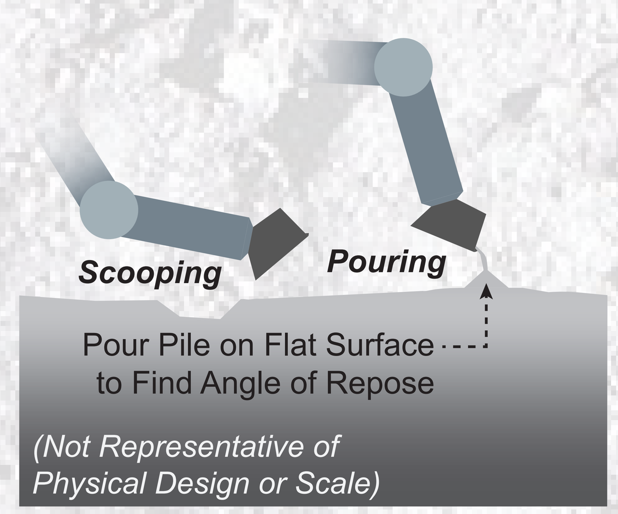

Figure 5. Diagram of Angle of Repose Test

Design of Experiments

The following set of experiments are proposed for finding several desired parameters using various mounted plates, sensors, and scoops on the end of an Universal Robotics (UR)-10 robotic arm. Each test is to be completed with three different lunar simulants (LHS-1 [2], GRC-3 [3], and BP-1 [4]) with three different density scenarios per simulant: at bulk density, at an average density between the min and max, and at the max density.

Site Prep for Regolith Microwave Sintering (Figure 1.)

Action: *A 2' by 2' pad will be built up with four 1" layers by excavating adjacent material, sieving the material, and depositing it on the pad site. A topography scan will be completed after each layer is deposited to measure volume, after which fine grading, compacting, and sintering activities can occur.*
Inputs: V_S *(Scoop Volume),* n_S *(Number of Scoops),* ρ *(Bulk Regolith Density)*
Outputs: V_L *(Layer Volume),* ρ_L *(Layer Density)*

Pressure-Sinkage Test (Figure 2.)

Action: *Slowly press down normal to regolith surface with bearing plate until desired or max allowable force (or max allowable displacement) is reached.*
Inputs: *P (Applied Pressure), b (Plate Width)*
Outputs: *z (Vertical Displacement)*

Shearing Test (Figure 3.)

Action: *Press down normal to regolith surface with bearing plate with grouser until desired load is reached, then translate horizontally by a set distance.*
Inputs: *A (Shearing Plate Area),* σ_n *(Applied Normal Load)*
Outputs: τ_s *(Shear Stress at Failure)*

Excavation Test (Figure 4.)

Action: *Approach regolith surface with scoop at desired rake angle, then vertically translate scoop cutting edge down into the regolith to the desired depth. Translate the scoop horizontally as needed (dependent on scoop depth & rake angle) then rotate up to collect sample.*
Inputs: β *(Rake Angle),* D_T *(Trench Depth),* L_T *(Trench Length)*
Outputs: L_S *(Surface Excavation Length),* F_t *(Tip Force),* T_t *(Tip Torque)*

Angle of Repose Test (Figure 5.)

Action: *Excavate desired volume of regolith then translate scoop diagonally over above a flat surface. Slowly angle the scoop to dump contents onto the surface at a relatively constant rate, creating a pile.*
Inputs: *V (Sample Volume),* n_S *(Number of Scoops),* d_d *(Drop Distance)*
Outputs: r_p *(Pile Radius),* h_p *(Pile Height)*

Data Analysis

Pressure-Sinkage Test
- Results from similar densities for different simulants and different starting densities per simulant will reveal bearing strength sensitivity's to density and composition properties
- Results can be inserted into Bernstein's [5], Reece's [6], and Bekker's [7] pressure-sinkage equations to solve for their constants (**k** and **n** from Bernstein's and $\mathbf{k_c}$, $\mathbf{k_\phi}$, & **n** from Reece's and Bekker's)

Shearing Test
- (Mohr-Coulomb shear str. at shear failure) $\tau_s = \sigma_n \tan(\phi) + c$
- (Sliding str. after shear failure) $\tau_a = \sigma_n \tan(\delta) + a$
- Results will allow for cohesion (**c**), adhesion (**a**), internal friction angle (**ϕ**), and the angle of external friction (**δ**) to be solved for

Excavation Test
- Results will facilitate calculation of the $\mathbf{N_\gamma}$, **Nc**, & **Nq** constants and the excavation force's frictional and adhesional components from the fundamental equation of earthmoving (FEE) by Hettiaratchi & Reece [8]. Equations from Luengo et al. [9] which handle shear, remolding and gravitational forces will also be used

Angle of Repose Test
- In line with ASTM standards C1444 and D6393, the inverse tangent of a poured soil pile's height over its radius will produce an angle of repose value for the surface regolith

Regolith Microwave Sintering Site Preparation
- Data from shear vane cone penetrometer tests on the pad easement will reveal design readiness for sintering operations

Conclusions

- Through quantification of the geotechnical properties of lunar regolith, a library of statistical parameter estimates and functional relationships can be generated, leading to informed planning of lunar infrastructure development

- Lab tests can be compared to equivalent lunar tests using a Commerical Lunar Payload Services (CLPS) lander mission

- Robust knowledge of the bearing and shear properties of lunar regolith will benefit the structural design of infrastructure, vehicles, and hardware that must rest on the lunar surface and decrease the risks posed to future missions and their personnel

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